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SUBJECT: Upstream PCB Transport from Green Bay West Facility

Summary

LimnoTech gathered data and conducted simulations to estimate the maximum potential upstream transport and settling distance for particles released from the Fort Howard Corporation (Green Bay West) mill during the historical period of PCB release from the recycling of carbonless copy paper. Understanding the movement of particles is important because PCBs in aquatic systems tend to bind to particles, and particularly to particles with high organic carbon content like those from paper-making processes. Upstream transport occurs because flows in the Lower Fox River can temporarily reverse in the face of certain combinations of low river flows and water level fluctuations in Green Bay (called seiches).

The full year 1970 was selected for the simulation, because it was a year of relatively low flow and of high seiche amplitudes. As a result of these characteristics, the modeled extent of upstream transport and settlement to the sediment bed represents a likely maximum. Historical shoreline configurations were incorporated in the simulation. The simulation model was calibrated to reproduce current velocities and water depths as measured in the Lower Fox at the mill location. Modeled settling rates of particles discharged from the mill were based on settling tests conducted using paper mill effluent. Modeled settling rates of particles discharged from settling ponds were based on engineering calculations and plant records. For each outfall, a conservative settling rate was selected for use in the model, from the range of estimates.

The end product of the simulation is a pair of maps showing the range of settling locations for particles discharged from the two historical process-water outfalls of the Green Bay West mill. The maps show that more than 99.9% of all particles discharged from the Green Bay West mill during the relevant period settled to the sediment bed of the river or bay downstream of a point approximately 400 feet south (upstream) of the upstream boundary of the Green Bay West mill. A sensitivity analysis demonstrated that changes in the shoreline at the mill location to accommodate clarifiers that went on line in 1972 make little difference in the extent of upstream transport and settlement.

The simulation did not include the effects of subsequent resuspension and transport. If particles settled to the sediment bed in the river, they could be resuspended and transported downstream by prevailing river flows. Because of the combination of conservative assumptions, the mapped footprints produced by the model provide a conservative estimate of the potential scope of upstream sediment impacts of releases from the Green Bay West mill.

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Description of Wastewater Process Streams and Discharge Locations

Historically, wastewater at the Green Bay West mill was produced by pulping and deinking operations, conducted in the southern portion of the facility, and papermaking operations, conducted in the northern portion of the facility. As is still true today, the majority of pulp used to create paper products at the plant was obtained from recycling of scrap paper. Pulping generates a wastewater stream with high solids content. Pulp generated in the pulping operation was transported to the papermaking operation, where it was blended with water and sprayed onto a series of conveyors that transformed the pulp into dewatered sheets. These sheets were dried and ultimately turned into paper. Papermaking generated wastewater with high solids content. A significant proportion of solids was removed from the wastewater stream by fiber-water separators called save-alls, after they were installed in 1957.

Wastewater flows from the processes described above, as well as cooling water flows, were discharged historically to the Lower Fox River via three outfalls. As the numerical designations for the outfalls have changed over the history of plant operation, they will be referred to in this memorandum as the North, Middle, and South outfalls.

Prior to 1972, wastewater flows from the pulping and de-inking process were treated by lime addition to enhance coagulation, followed by settling in a series of ponds at the south end of the property. Following settling, the effluent was decanted and discharged to the river via the South outfall. In 1972, clarifiers were added to the treatment operation, followed by aeration and secondary clarification to be applied to the pulping and de-inking wastewater stream. Discharge continued to be through the South outfall.

Prior to 1972, all wastewater flows from the papermaking operation were discharged directly from the save-alls to the river via the North outfall. Emergency overflow from the papermaking operation was also sent to the North outfall. In 1972, flows from the papermaking operation were diverted to the on-site wastewater treatment operation, where the water was treated by primary clarification. Flows were then combined with treated effluent from the pulping and de-inking operation and discharged via the South outfall.

A third stream of non-contact cooling water was discharged from the Middle outfall during this period, with no known changes in operation. Records from 1978 also indicate that storm water from the mill was discharged to the river via the North outfall.

Direction of Flow

Solid particles discharged from the Green Bay West Mill into the Lower Fox River during the historical period of PCB discharge were transported either upstream or downstream in the river, with their direction, velocity, and path depending on river flow and the rate at which discharged particles settled to the bottom. Upstream transport is possible in the Lower Fox due to reversals of current that occur under low flow conditions.

The cause of the reversals is a phenomenon called a seiche, which is a wind-driven oscillation in water surface elevation. Winds blowing over Green Bay exert friction on the water surface, and this drives water at the surface in the direction that the wind is blowing, causing the water surface to slope upward in that direction. As the wind subsides, the water surface at one end of Green Bay drops and the surface at the other end of the Bay rises. The process then reverses, and the water level at each end of the bay cycles repeatedly up and down. The amount of time that it takes for the water level at either end of the bay to complete one cycle of oscillation is called the seiche period. Oscillations in Green Bay have a characteristic period of 10.8 hours. Additional oscillations of lesser amplitude also occur in Green Bay,

due to a seiche in Lake Michigan, and also due to the moon's gravitational pull, each having different characteristic periods.

The Lower Fox River is affected by these water surface oscillations in the lower reach that discharges into Green Bay, similar to the way in which water levels rise and fall in a coastal estuary due to tides. A progressive wave enters the river, causing the water surface to rise, and this pressure wave travels upstream. Current velocity is affected because the presence of the wave alters the slope of the water surface. Under high-flow conditions, the slope of the water surface from upstream to downstream is sufficiently steep that the effect of the progressive wave is simply to reduce the current velocity in the river without changing its direction. If base flow in the Lower Fox is sufficiently low, however, the presence of the wave can cause the water surface to briefly reverse its slope. This can occur during the time in the cycle when the water level at the mouth is near its peak, typically for 1-2 hours or less. A reversal of slope causes flow to move in the upstream direction. The distance that suspended material can be carried upstream is limited by the duration of the flow reversal and by the upstream velocity during the flow reversal. As the water level at the mouth falls from its peak, flow in the downstream direction is restored, and materials that remain in suspension reverse their direction and are transported downstream.

The seiche is documented by water-level measurements taken at the Lower Fox River mouth by the National Oceanic and Atmospheric Administration (NOAA). These data have been collected on an hourly basis since 1970 and every 6 minutes since 1990. Georgia-Pacific also deployed an acoustic Doppler current profiler (ADCP) in the navigation channel near the Green Bay West facility to measure current velocity between December 14, 1999 and January 4, 2001. Complete data for this period were obtained except between June 21 and August 16, 2000, a period of instrument malfunction. The ADCP measured velocities every 15 minutes at six water depths, ranging from 0.85 to 3.85 meters above the sediment bed. A pressure transducer was also installed at the adjacent west bank bulkhead to measure water level. Figure 1 illustrates the water level and velocity data obtained from these deployments for a single week in May 2000. The top panel shows that there were multiple daily oscillations in water surface elevation, and the bottom panel shows the resulting oscillations in stream velocity. The lower panel shows that velocity also oscillated multiple times per day, and became negative (indicating flow reversal) for a number of short periods during the week that were coincident with times of peak water surface elevation.

Four Vector Averaging Current Meters (VACMs) were also installed in positions that flanked the ADCP location from bank to bank, between September 6 and October 17, 2001, and the ADCP was redeployed during this period. This was done to collect additional information on variations in current velocity along a river cross-section. Locations of the ADCP and the VACMs are shown in Figure 2. Measurements of velocities and water levels were used to calibrate a model of flows in the Lower Fox River, as described below.

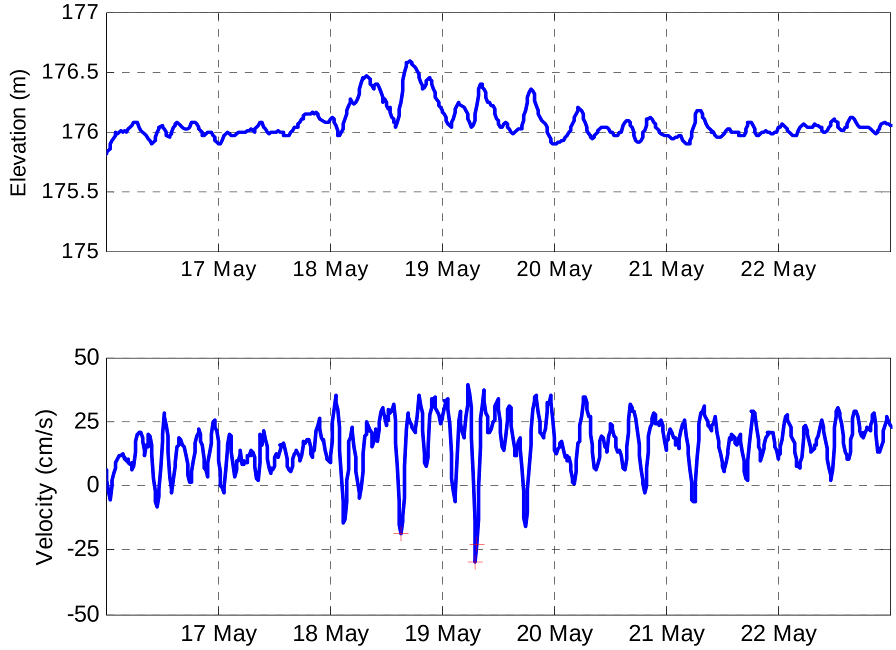

Figure 1: Water Surface Elevation and Depth-Averaged Downstream Velocity Measured at Green Bay West Plant Location, May 16-23, 2000

Estimated Settling Rates

In addition to current velocities, estimates were made of the rates at which historical solid particles discharged from the North and South outfalls settled in the river. Solid particles in rivers settle toward the bottom as they are carried upstream or downstream by the current, and the rate at which they settle is expressed as a distance traveled toward the bottom per day in the river. The settling rate describes how quickly a particle settles to the bottom, and therefore how long it remains in suspension as it is carried up- or downstream. Larger, heavier particles like those discharged from papermaking operations via the North Outfall settle more rapidly, while smaller, lighter particles like those discharged from the settling ponds via the South Outfall settle more slowly. As they settle, particles can bind together into bigger particles, called floc, and this process of flocculation causes the growing particles to settle faster.

Understanding the movement of particles is important because PCBs in aquatic systems tend to bind to particles due to their chemical nature, especially to particles with high organic carbon content such as those from paper-making processes. Particle settling rates for paper mill effluent from the North Outfall were estimated through a particle settling test. Samples of paper mill effluent were collected from the Green Bay West mill on October 30, 2000. Samples were collected from the wastewater lines before primary treatment so that they were similar in character to the effluent that was discharged from the North Outfall under historical operating conditions, prior to the implementation of primary settling in 1972. To provide dilution water for the settling tests that are described below, water samples from the Lower Fox River were also obtained on the same date.

Effluent samples were transported in a temperature-controlled truck to an ARCADIS laboratory for flocculent settling testing. This test allows small particles to coalesce into larger particles as they would in a river, and also included mechanical mixing prior to introducing the samples to the settling columns, to approximate the way that turbulent river energy affects flocculation. Samples were diluted to 20% using four volumes of filtered Lower Fox River water per volume of effluent. This was the estimated rate of dilution that would have occurred at the point of discharge, as estimated by simulating discharge from the North Outfall using a USEPA-approved model called the Cornell Mixing Zone Expert System (CORMIX). Temperature was carefully controlled during the settling tests.

Settling tests indicated that settling rates for paper mill solids ranged as high as 180 meters per day, with a median settling rate of about 100 m/day. The overwhelming majority of particles (about 80% by mass) settled at a rate exceeding 40 meters/day. It is not practical to use many settling rates in the simulation, so a settling rate of 40 meters per day was conservatively selected to represent the lower range of settling rates of North Outfall particles. At this rate, a particle released from the North Outfall would settle from the water surface to the bottom of the river (to a depth of about 10 feet) in about 2 hours. In contrast, a particle settling at the median rate of 100 meters per day would settle by 10 feet in a shorter time, less than 45 minutes. This would prevent it from traveling as far upstream during a seiche. Thus, the lower assumed settling rate of 40 meters per day is a more conservative choice for the North Outfall.

A settling rate for solids discharged from the settling ponds via the South Outfall was estimated by Arcadis (2001), on the basis of documented flows and on the geometry of the settling ponds. Settling ponds capture the particles in waste water that settle most rapidly, so that the remaining particles discharged from a settling pond are relatively light and slow to settle. The settling velocity of particles discharged from a settling basin can be estimated as the ratio of influent flow to area, called the "overflow rate" (Metcalf and Eddy, 1991) Particles with settling rates exceeding the overflow rate are captured by the settling pond, while particles with lower settling rates remain in suspension long enough to be discharged with outflow. Arcadis estimated overflow rates ranging from 2.3 to 4.8 m/day based on flow records for the years 1965-1972. At these rates, particles from the South Outfall would have settled at a rate of less than one foot per hour, so that during a typical flow reversal lasting only a few hours, most particles would have remained in suspension long enough to reverse their direction and deposit downstream.

While a lower settling rate is the conservative choice for the North Outfall, a higher settling rate is more conservative for modeling the lighter particles from the South Outfall. The heavier particles discharged from the North Outfall settled rapidly enough that they could reach the river bottom during a larger seiche event. The lower the settling rate, the longer these particles remained in suspension, giving them the opportunity to travel farther upstream and deposit during the event. In contrast, particles from the South Outfall were so light as to settle very little during a single seiche event, relative to the depth of the river. A lower settling rate for South Outfall particles would only have increased the likelihood that those particles would have remained in suspension for the duration of the seiche event, returning downstream. Therefore, for the South Outfall, a higher settling rate is the more conservative assumption, increasing the likelihood that simulated particles settle upstream during seiche events.

Sensitivity analyses conducted with the model described below showed that upstream impacts were indeed greater when particles released from the South Outfall were assigned settling velocities at the higher end of the estimated range (2.3 to 4.8 m/day). A settling rate of 5 m/day was therefore selected to yield a reasonable maximum upstream distance that particles from the South Outfall may have traveled before settling to the sediment bed.

Hydrodynamic and Particle Tracking Model

After estimating the settling rates of particles released from each outfall, the next step was to simulate their deposition on the river bottom, taking into account the direction of the current and its velocity. The objective of the modeling described below was to map the locations where particles initially settled to the sediment bed after discharge. Resuspension of sediments also occurs at high flows, when velocity is sufficiently high to scour material from the sediment surface. In the Lower Fox River, sufficiently high velocities for scour to occur are common for downstream flows, and are rare for reverse flows, as confirmed by the velocity monitoring that Georgia-Pacific has conducted. Thus, the cumulative effect over time of resuspension is to move sediments in the downstream direction. The simulations did not include this subsequent resuspension and transport. As a result, particles discharged from the Green Bay West mill outfalls may no longer be present at the settling locations shown by the simulations, having been resuspended and transported downstream. In this way the deposition footprints produced by the particle tracking model provide a conservative estimate of the potential scope of upstream sediment impact from Green Bay West particles.

The transport, settling, and deposition of a particle discharged from the plant outfalls is governed by hydrodynamics, as influenced by the seiche, and the competing effect of downstream flow coming from the watershed. Particle transport is also influenced by the varying bathymetry of the bed and by shoreline characteristics. Consequently, a three-dimensional modeling study was performed to simulate the multidimensional velocity structure in the river and to quantify its effects on particle transport and deposition.

A three-dimensional hydrodynamic model was developed for the reach of the Lower Fox River from DePere Dam to the mouth using a program (3DD) that was developed by Black (1995), which has been used extensively in peer-reviewed hydrodynamic applications. Inputs to the 3DD model included flows as measured at the USGS gage at Rapide Croche, water levels at the mouth as measured by NOAA, a bathymetric survey conducted by Ocean Surveys in 1998, and shoreline representations based on NOAA navigation charts. The 3DD model was initially calibrated to the 2000 dataset, including the level sensor located at the Green Bay West bulkhead and the velocity data from the ADCP. The calibration was then refined using data from September and October of 2001, including the four VACMs, in addition to data for the same period from the ADCP and level sensor. The calibration of the hydrodynamic model showed that the model accurately captures the timing and magnitude of velocity fluctuations driven by the Green Bay seiche.

The calibrated hydrodynamic model was then used to drive a three-dimensional particle tracking model that was developed to work in concert with 3DD, called POL3DD (Black and Gay 1989, Black 1994). 3DD and POL3DD have been extensively used in combination in peer-reviewed hydrodynamic and particle transport applications. The POL3DD model simulates the release of particles from the North Outfall, settling at a rate of 40 m/day, and from the South Outfall, settling at a rate of 5 m/day. As they settle, particles are subject to upstream and downstream advective transport (i.e. as they are conveyed by the current) in addition to transport due to dispersive mixing in the turbulent river, both of which are simulated by the 3DD model.

Full Year Simulation – 1970

To estimate the range of transport and settling distances for particles released from the North and South Outfalls, a simulation was conducted. To capture the full range of seasonal flow and water level variability, a full year was simulated.

To select a year, water level and flow data for the period of historical PCB discharge were reviewed. Water levels at NOAA's Green Bay station were evaluated for the period 1970-79, 1970 being the first year for which continuous water level data are available. The year 1970 was selected as a conservative choice for the simulation because it included relatively high seiche amplitudes and relatively low average flows, both of which tend to favor upstream transport. Average flows in the Lower Fox River were also lower in 1970 than the years 1965-69. Thus, simulating another year between 1965 and 1969 would likely have resulted in a footprint extending less far upstream. In addition, the year 1970 was estimated by Wisconsin Department of Natural Resources (WDNR) to be the peak year of PCB discharge from the Green Bay West Mill (WDNR, 1999).

Following calibration of the 3DD hydrodynamic model to the September/October 2001 dataset, the model was applied to simulate the full year 1970. In order to represent 1970 conditions, model bathymetry and shorelines were modified to reflect the 1970 shoreline configuration. Figure 2 shows the evolution of the shoreline in the plant area, including a build-out that occurred upstream of the South Outfall. The shoreline evolution presented here is based on historic aerial photos that bracket the 1970 simulation period, including a navigation chart dated 1969 and a photo taken in 1971. The backdrop to the figure is a 2008 aerial photo representing the current shoreline.

The 1970 simulation used the shoreline represented in a 1969 NOAA navigational chart as the best available estimate of shoreline conditions at the time. As shown in Figure 2, additional land infilling was completed by 1971, resulting in a migration of the shoreline approximately 80 m to the south. The sensitivity of the model to this shoreline change is discussed below.

Results of the 1970 simulation, using the shoreline shown in the 1969 NOAA chart, are shown in Figures 3a (North Outfall) and 3b (South Outfall). In each figure, 99.9% of particles discharged from the referenced outfall settled initially within the shaded area. Figure 3a shows that 99.9% of simulated particles released from the North Outfall initially settled in the area downstream of the current Green Bay West bulkhead located at the upstream (southern) boundary of that facility. Figure 3b shows that 99.9% of simulated particles released from the South Outfall initially settled in the area downstream of a point located about 400 feet upstream of the Green Bay West bulkhead at the southern property boundary. The upstream portions of the footprints do not extend to the east side of the river. The maps also include the present-day shoreline of the Lower Fox River.

Sensitivity to Assumed Shoreline

As described above, the full year 1970 simulation included the shoreline as represented in a 1969 NOAA chart in order to represent the river geometry as it was 40 years ago. The progress of shoreline evolution in Figure 2 shows that additional shoreline build-out occurred by the time of the 1971 aerial photo, to accommodate the clarifiers that went on line in 1972. The exact timing of the build-out is uncertain.

To evaluate sensitivity to this difference in shoreline, LimnoTech compared simulations of a high-seiche period in May of 1970, using both the current shoreline (per the 1998 NOAA chart) and the 1969 NOAA shoreline. The 1969 and 1998 shorelines are shown in Figure 2. The upstream limit of transport (based on the 99^{th} percentile of particles deposited) was compared between the two simulations. The difference in simulated upstream particle excursions due to the shoreline change was only the length of a single model cell (+/-40 meters). For South outfall release, the difference with the 1998 shoreline was transport 40 m farther upstream, while for the North outfall release, the difference was a reduction of 40 m in upstream transport. The actual sensitivity of particle transport to shoreline changes that occurred between 1969 and 1971 would be less than 40 meters, given that build-out that occurred during this period was smaller than the changes that occurred between 1969 and 1998.

Conclusion

A modeling study has estimated how far upstream particles released from the Fort Howard Corporation (Green Bay West) mill traveled before depositing on the sediment bed. Peer-reviewed modeling methods were used, and the model used detailed data on flows and water levels collected the mill location, as well as laboratory and engineering studies of particle settling speeds. The selection of assumptions was conservative with respect to the year that were simulated; the particle settling rates that were used; and the modeling of initial settling only, not including subsequent resuspension and downstream transport. Because of the extensive use of data and peer-reviewed models, and the conservatism of the assumptions, the boundaries can be accepted with confidence as upstream limits of particle transport and potential impacts on the sediment bed.

References

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Figure 2: Historical Shoreline Evolution near Fort Howard Plant, ca. 1970, and 2001 VACM / ADCP Monitoring Locations

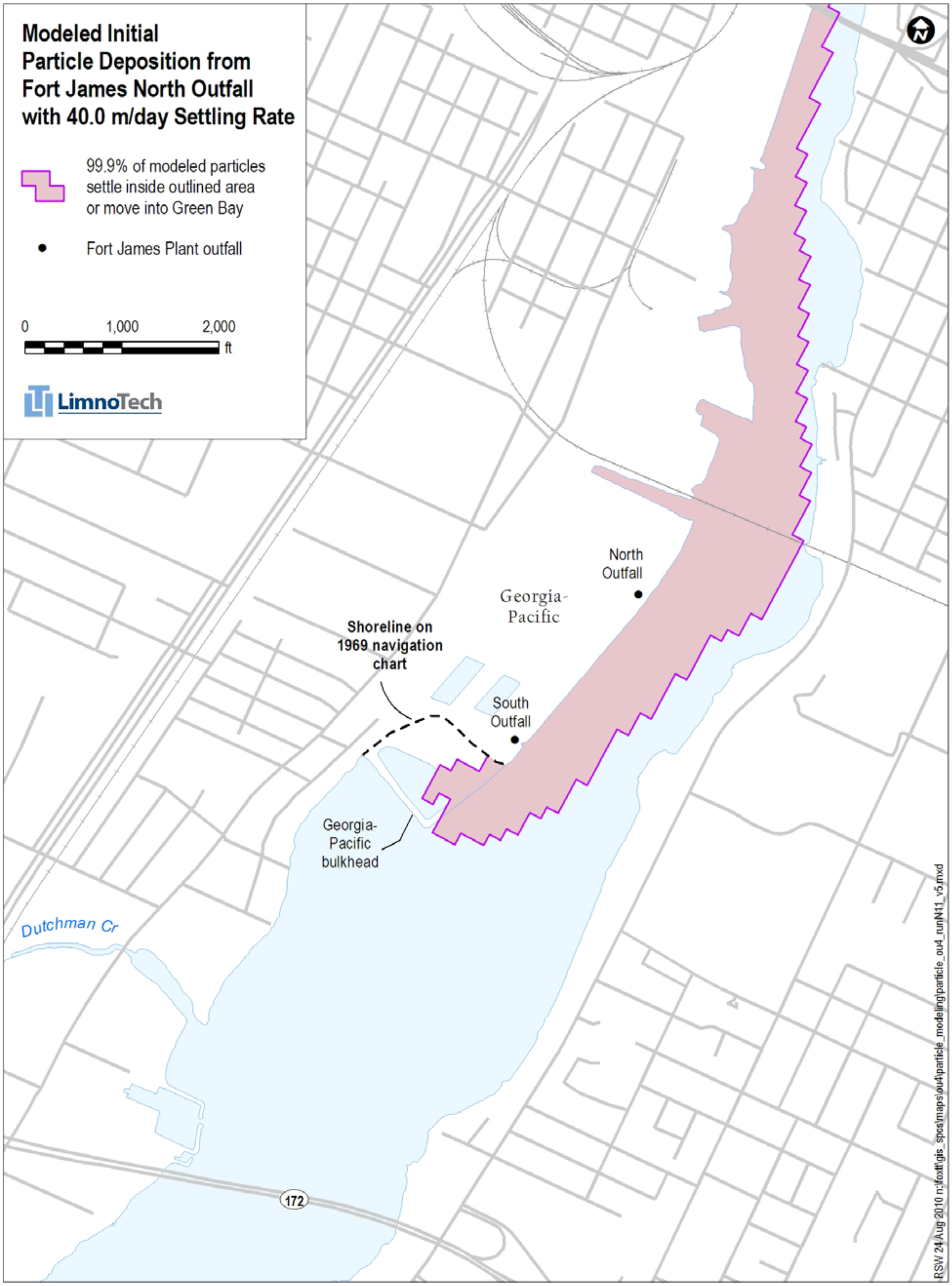

Figure 3a. Extent of Particle Deposition for North Outfall (Settling Rate = 40 m/day)

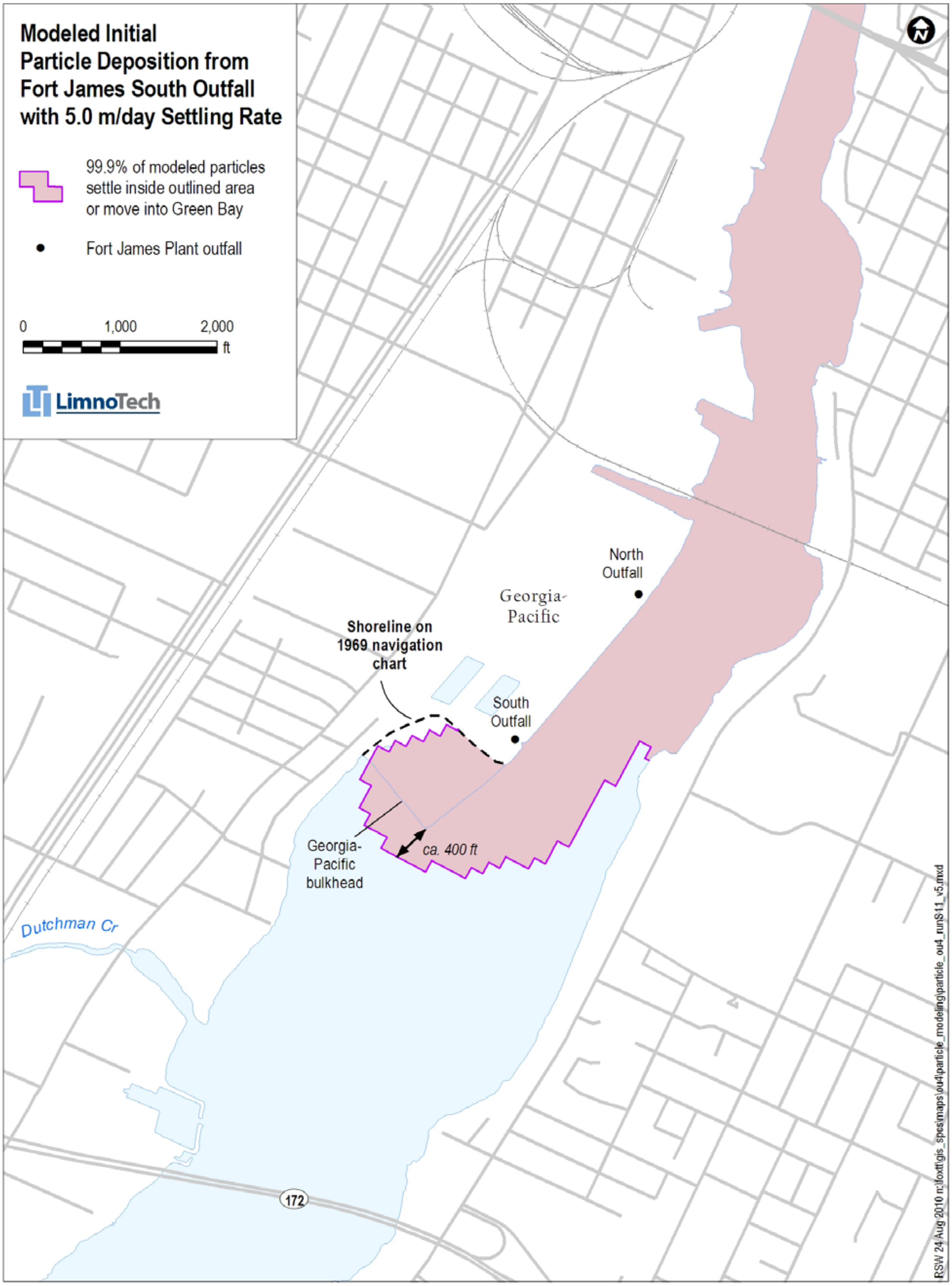

Figure 3b. Extent of Particle Deposition for South Outfall (Settling Rate = 5 m/day)